HIGHLY OXIDIZED AND METAMORPHOSED CHONDRITIC OR IGNEOUS (?) CLASTS IN THE CV3 CARBONACEOUS CHONDRITE MOKOIA: EXCAVATED MATERIAL FROM THE INTERIOR OF THE CV3 ASTEROID OR PREVIOUSLY UNSAMPLED ASTEROID.

[1]Krot A. N. and [2]Hutcheon I. D. [1]Hawai'i Institute of Geophysics and Planetology, SOEST, University of Hawaii at Manoa, Honolulu HI 96822, USA; [2]Isotopic Science Division, Lawrence Livermore National Laboratory, Livermore CA 94551, USA.

ABSTRACT. The Mokoia clasts are fragments of coarse-grained, granular, polymineralic rocks which consist of Ca-rich fayalitic olivine (Fa_{37}, ~0.4 wt.% CaO), Fe-rich Al-diopside ($Fs_{11}Wo_{49}$, ~4 wt.% Al_2O_3), anorthitic plagioclase ($An_{46-81}Ab_{54-19}$), nepheline, Fe-rich Cr-spinel [fe = $Fe_{tot}/(Fe_{tot}+Mg)$ = 0.68-0.77, cr = Cr/(Cr+Al) = 0.26-0.41], pyrrhotite, pentlandite, and rare grains of Ni-rich taenite. Nepheline typically replaces plagioclase. The textures and mineralogy of the clasts indicate that they were extensively metamorphosed above 750-800°C prior to excavation from their parent asteroid and subsequently added to the Mokoia breccia; the last event postdates aqueous alteration of the host meteorite. The coexisting Al-diopside, anorthitic plagioclase and Cr-spinel in the clasts and high CaO contents in olivine suggest that precursor materials for the clasts were rich in Ca and Al; Fe-rich compositions of olivine, diopside, and mineralogy of the opaque assemblage suggest a high degree of oxidation. The mineralogy and mineral chemistry of the Mokoia clasts are unique among known metamorphosed ordinary and carbonaceous chondrites and achondrites and may represent material from a previously unsampled asteroid. Alternatively, the Mokoia clasts may have been excavated from the oxidized and metamorphosed interior of the CV3 asteroid.

INTRODUCTION. Recrystallized, granular chondrules (Type R) consisting of compositionally uniform olivine, clinopyroxene, and nepheline were discovered in Mokoia more than a decade ago [1], but have not received any attention since then. Cohen et al. [1] considered two models of their origin: asteroidal and nebular. According to the asteroidal model, these chondrules were metamorphosed in a planetesimal and subsequently plucked out of the metamorphic rocks and mixed with Mokoia material during brecciation. According to the nebular model, preferred by Cohen et al. [1], these chondrules formed by recrystallization of fine-grained dust aggregates during sintering in the solar nebula. During our systematic study of the alteration features in CV3 chondrites [2], we found that the equilibrated clasts, described by Cohen et al. [1] as Type R chondrules, are common in all Mokoia thin sections, have unusual ferromagnesian chondrule mineralogy and, in addition to nepheline, contain abundant anorthitic plagioclase that makes them potentially interesting for I-Xe studies and search for initial abundances of ^{26}Al. Plagioclase-nepheline-bearing chondrules and clasts have previously been described in ordinary and carbonaceous chondrites, however, their origin remains unclear [e.g., 3-6]. In this paper, we describe the mineralogy and petrography of the plagioclase-nepheline-bearing clasts in Mokoia.

PETROGRAPHY AND MINERALOGY. The Mokoia clasts are coarse-grained (20-100 µm), granular, polymineralic rocks, up to 2 mm in size, consisting of fayalitic olivine, Fe-rich diopside, anorthitic plagioclase, nepheline, Cr-spinel, sulfides, and rare grains of Ni-rich taenite. Olivine and pyroxene are the major minerals in the clasts; they typically form aggregates with 120° triple junctions indicative of extensive recrystallization. In some cases, subrounded olivine grains are poikilitically enclosed in pyroxene. Plagioclase fills interstitial regions between olivine and pyroxene grains or surrounds pyroxene grains; it also forms inclusions in olivine. Nepheline or a nepheline-like phase is located preferentially in the peripheral zones of the clasts, where it fills interstitial regions between olivine and pyroxene crystals or replaces plagioclase. Subhedral and euhedral grains of Cr-spinel occur as inclusions in olivine and pyroxene and commonly form intergrowths with sulfides. Although all major components in Mokoia are aqueously altered and contain ubiquitous phyllosilicates and magnetite [7], minerals in the clasts were not affected by aqueous alteration.

Fayalitic olivine grains are compositionally uniform ($Fa_{37\pm1}$, n=60) and have very high CaO contents (0.41±0.13 wt.%) and moderate contents of MnO (0.25±0.03 wt.%); Al_2O_3, TiO_2 and Cr_2O_3 are <0.05 wt.%. Fe-rich diopsides ($Fs_{11\pm1}Wo_{49\pm1}$, n=35) have uniformly low MnO 0.08±0.02 wt.%), average Na_2O (0.53±0.05 wt.%) and Cr_2O3 (0.83±0.13 wt.%), and relatively high and variable TiO_2 and Al_2O_3 contents (1.0±0.4 and 3.7±1.4 wt.%, respectively). Cr-spinel grains (cr = 0.26-0.41, n=15) are Fe-rich (fe = 0.68-0.77) and uniformly enriched in TiO_2 (2.4±0.5 wt.%). In contrast to plagioclase that varies significantly in composition ($An_{46-81}Ab_{54-19}$) and contains <0.1 wt.% K_2O, nepheline or a nepheline-like phase has rather uniform composition and contains ~2 wt.% K_2O and ~ 3 wt.% CaO. Sulfide grains consist of Ni-poor (<0.3 wt.%) pyrrhotite and Co-bearing pentlandite (22-28 wt.% Ni, 0.7-1.7 wt.% Co).

DISCUSSION. The granular textures of the Mokoia clasts with 120° triple junctions between olivine and pyroxene crystals and uniform compositions of olivine and pyroxene clearly indicate that they experienced thermal metamorphism strong enough to equilibrate not only olivine but diopside as well. The estimated equilibration temperature, based on the clinopyroxene [8] and olivine-spinel thermometer [9], is ~750-800°C. The significant compositional variations of plagioclase are commonly observed in metamorphosed basaltic eucrites [A. Yamaguchi, pers. comm.] and are consistent with slow diffusion rates of $Ca^{2+} + Al^{3+} \leftrightarrow Na^{+} + Si^{4+}$ in plagioclase.

There is a general consensus that aqueous alteration that affected Mokoia and other CV3 chondrites and resulted in the formation of phyllosilicates and magnetite took place in the CV3 asteroid [e.g., 7, 11]. The absence of phyllosilicates and magnetite in the equilibrated clasts indicates that these clasts were added to the Mokoia breccia after the last hydration episode and, hence, are foreign material. The key question to be answered is what the precursor material is of the Mokoia clasts, and whether they are from the CV3 or some other parent asteroid.

There are several groups of ordinary and carbonaceous chondrites that experienced strong thermal metamorphism (e.g., H, L, LL, and CK). The highly oxidized mineral assemblage of the Mokoia clasts, average Fa content in olivine ~37 mol.%, which is significantly higher than even in olivine of LL6 chondrites ($Fa_{<35}$) [12], probably exclude ordinary chondrite (OC) material as the precursors for the clasts. This conclusion is also supported by the Al-rich compositions of Cr-spinel in the clasts (cr = 0.26-0.41); chromites in equilibrated OCs are typically Al-poor (cr = 0.85-0.95) [13]. The mineralogy of the clasts is also inconsistent with their origin in the CK asteroid. Although Fe-rich diopsidic pyroxenes compositionally similar to those in the clasts are common in many equilibrated CKs, the latter have more magnesian olivine, less An- and more Or-rich plagioclase and different opaque assemblages than those in the clasts, including magnetite, ilmenite, Ni-rich pentlandite, and troilite [14, 15].

The coexisting Al-diopside, anorthitic plagioclase and Cr-spinel in the clasts and high CaO contents in their olivine suggest that the precursor material for the clasts was Ca- and Al-rich. The Fe-rich compositions of olivine, diopside, and mineralogy of the opaque assemblages indicate its high degree of oxidation. The mineralogy and mineral chemistry of the Mokoia clasts are unique among known metamorphosed ordinary and carbonaceous chondrites and achondrites and may represent material from a previously unsampled asteroid. Alternatively, the Mokoia clasts may have been excavated from the oxidized and metamorphosed interior of the CV3 asteroid. Study of oxygen isotopic compositions of the clasts is required to answer this question.

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